Cryogenic scintillation properties of *n*-type GaAs for the Direct Detection of Sub-GeV/c^2 Dark Matter

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Outline

- Evidence for dark matter
- What we know and don't know
- Lee-Weinberg theorem: WIMPS > 2 M_P
- Large-scale > 10 M_P nuclear recoil (NR) experiments
  LiqXe, LiqAr, NaI(Tl)
- NaI(Tl) signal (DAMA experiment)
- "light DM" NR experiments with lower energy thresholds
- New theories: DM could be as light as M_e
- Electron recoil (ER) for M_e to M_P
- ER rate for different scintillators
- Scintillating GaAs (1.5 eV direct gap, >100 ph/keV, no afterglow?)
- Future prospects

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Lee-Weinberg dark matter bounding theorem

Lee and Weinberg, Phys Rev Lett, 39 (1977)

"The DM annihilation cross section is the order of m^2/M^4, where m is the DM mass and M is the Z-boson mass. DM below 2 GeV/c^2 would freeze out (stop interacting) early and their relic density would have caused the universe to collapse."

=> motivation for nuclear scattering experiments because energy transfer to the target is greatest when its mass is similar to the DM mass. M_{Xe} = 131, M_{Ar} = 40

=> Many ton-yr in liquid Xe, Ar. Why no interactions?
- Interaction rate < solar neutrino floor?
- Looking in the wrong mass range?

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New theory

- 2018 U.S. DOE Basic Research Needs Report:

"If dark matter is produced by thermal processes in the early universe, its mass must be greater than the electron mass (0.5 MeV) and less than about 100 TeV (10^{14} eV)"

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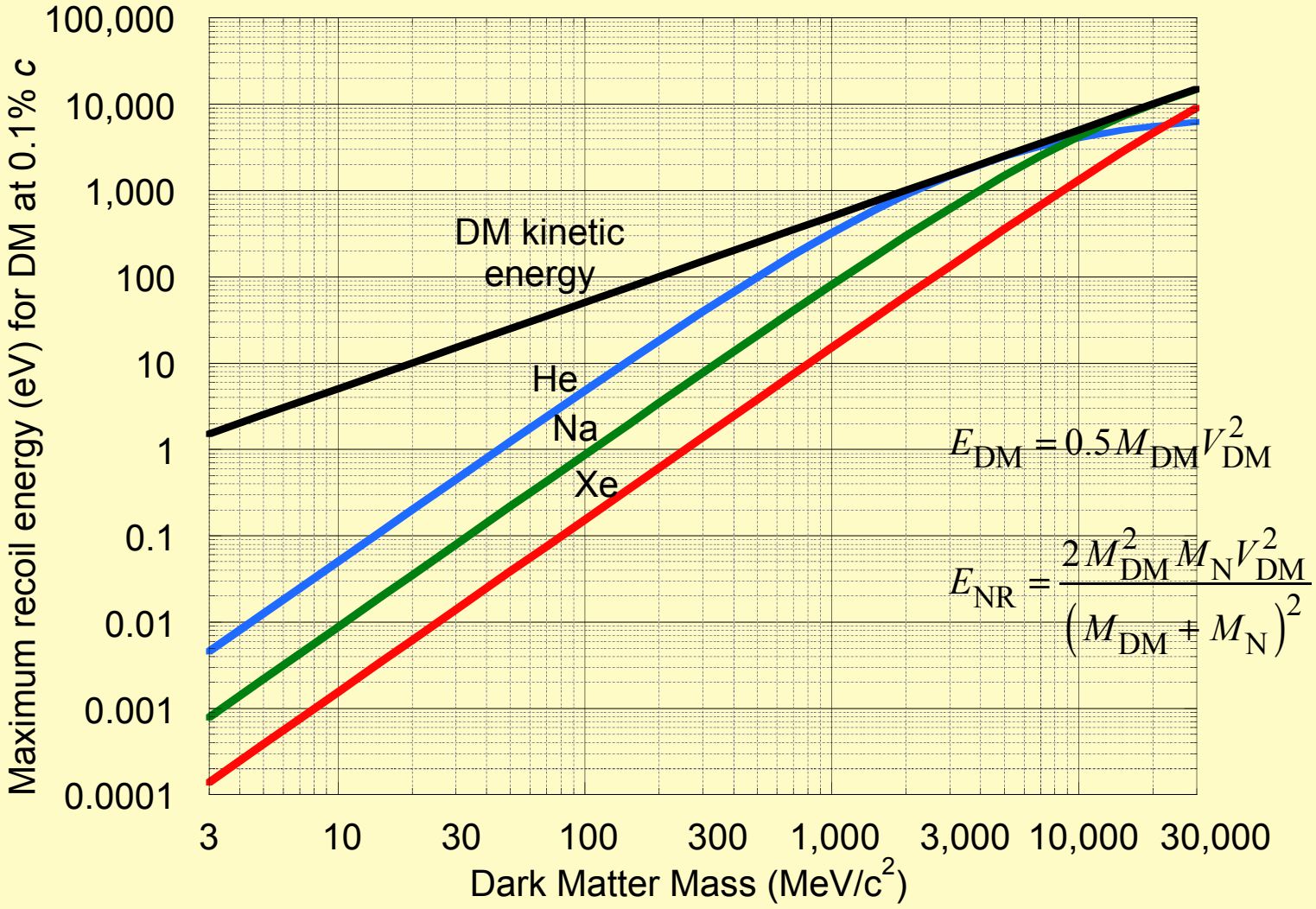
Maximum elastic NR energies ($v = 10^{-3}$ c)



The NR energy is very small for light DM and decreases as M_{DM}^2

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To detect lighter DM, need a lighter target

- Rouven Essig (UNY Stonybrook theorist) suggested that if DM particles are light, they could be producing large numbers of recoil electrons in existing NR experiments, BUT WOULD BE REJECTED.
- NR experiments reject anything that looks like a beta or Compton scattered electron.
- Rouven contacted me (though Craig Woody BNL) about the idea of scintillator targets. Together we wrote a paper exploring the capabilities of scintillators with different band gaps.
- ER kinematics is different than NR:
  - The ER energy spectrum peaks at the band gap of the scintillator.
  - If Si, Ge, or GaAs could be made to scintillate, they would have about ten times the event rate per kg-yr of NaI or CsI.

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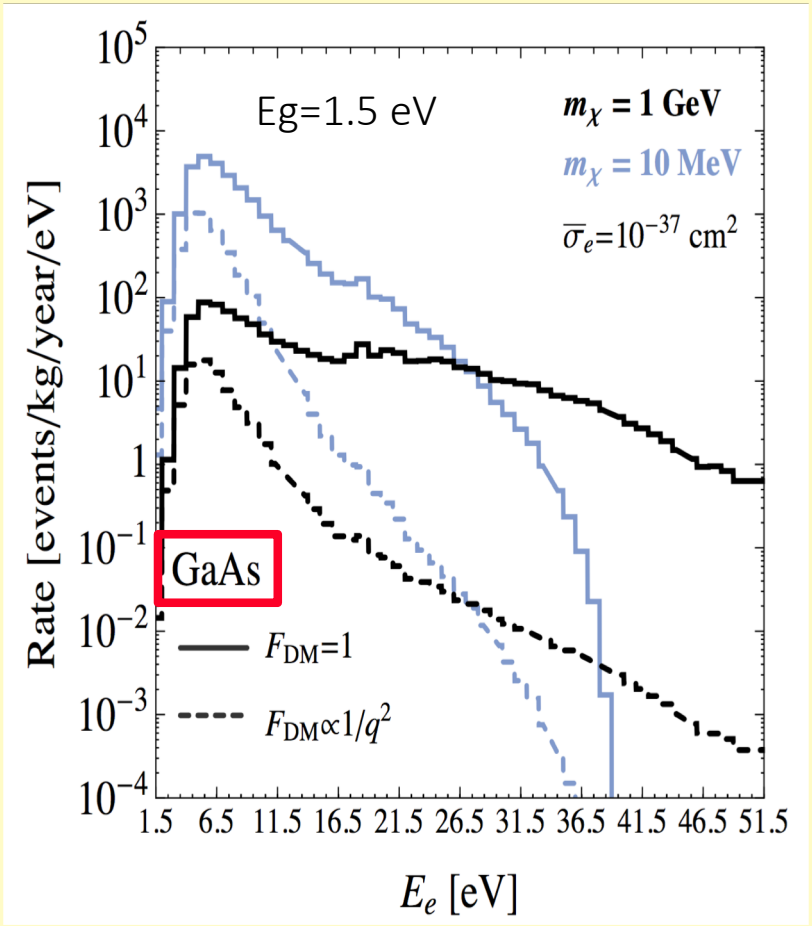
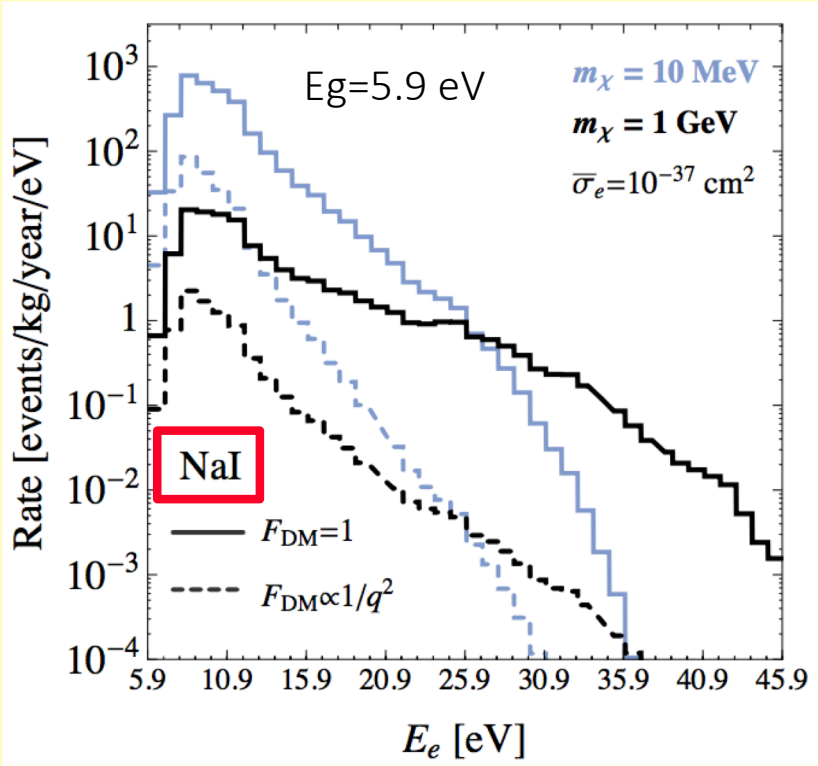
Event Rates vs. Electron Recoil Energy





Derenzo et al. "Direct Detection of sub-GeV Dark Matter with Scintillating Targets", Phys Rev D, 96, 016026, 2017 [arXiv:1607.01009]

- ER spectrum depends on E_g, M_{DM} and F_{DM}
- Higher rates with lower E_g of GaAs
- Most interactions produce few photons
- Low backgrounds very important

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Can Si or Ge or GaAs be made to scintillate?

- I found a 55 year old paper that reported donor-acceptor luminescence in GaAs.
- Si or Ge are indirect and not promising.
- Edith Bourret provided several GaAs wafers from her previous work.
- DC and Pulsed X-ray excitation showed promising scintillation
- "Cryogenic scintillation properties of n-type GaAs for the direct detection of MeV/c^2 dark matter" arXiv:1802.09171, J Appl Phys 123 (2018).
- => GaAs(Si,B) has good cryogenic scintillation properties:
    - Band gap 1.52 eV
    - No naturally occurring radioactive isotopes
    - Operates <100 K
    - High luminosity without antireflection coatings
    - Commercially grown as 5 kg crystals.
    - Donor electrons do not freeze out above a free-carrier concentration of 8 x 10^{15}/cm^3.
    - No afterglow

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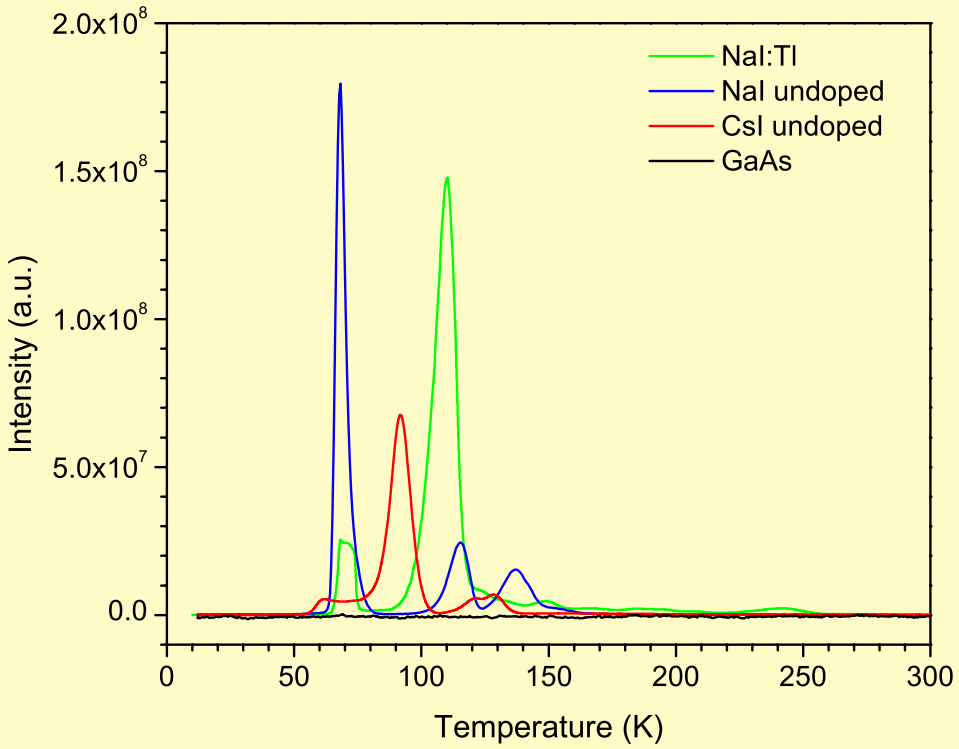
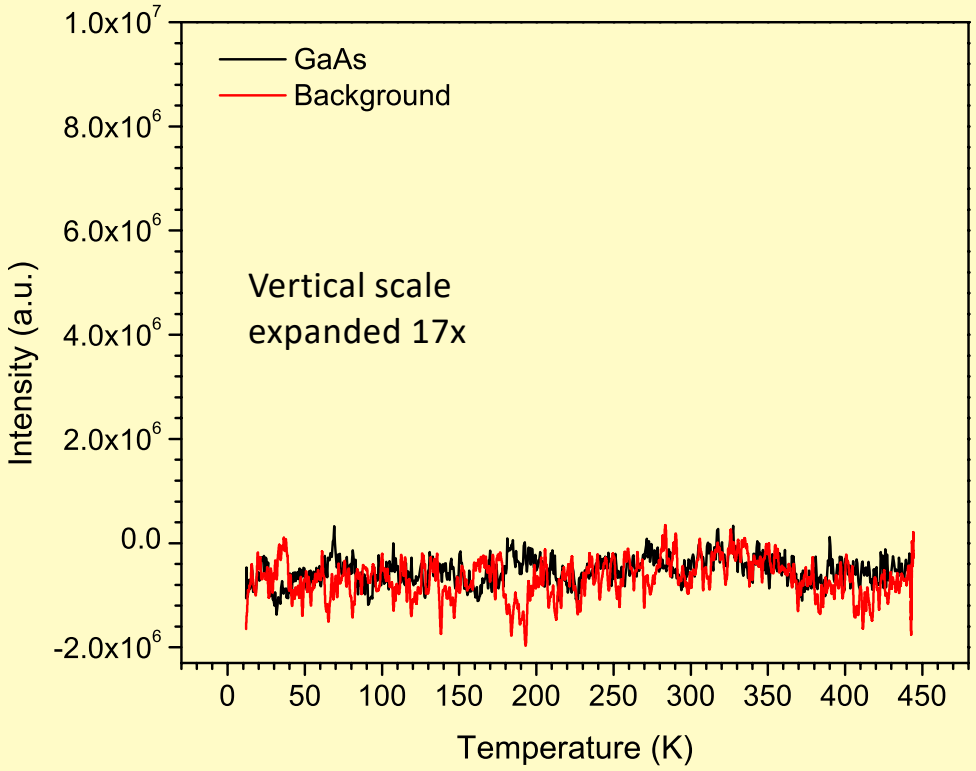
Afterglow: thermally stimulated luminescence

1) 50 keVp X-ray bombardment 10K for 30 minutes
2) Record stimulated emission T => 450 C





Any trapped holes in n-type GaAs annihilated by delocalized electrons => no afterglow

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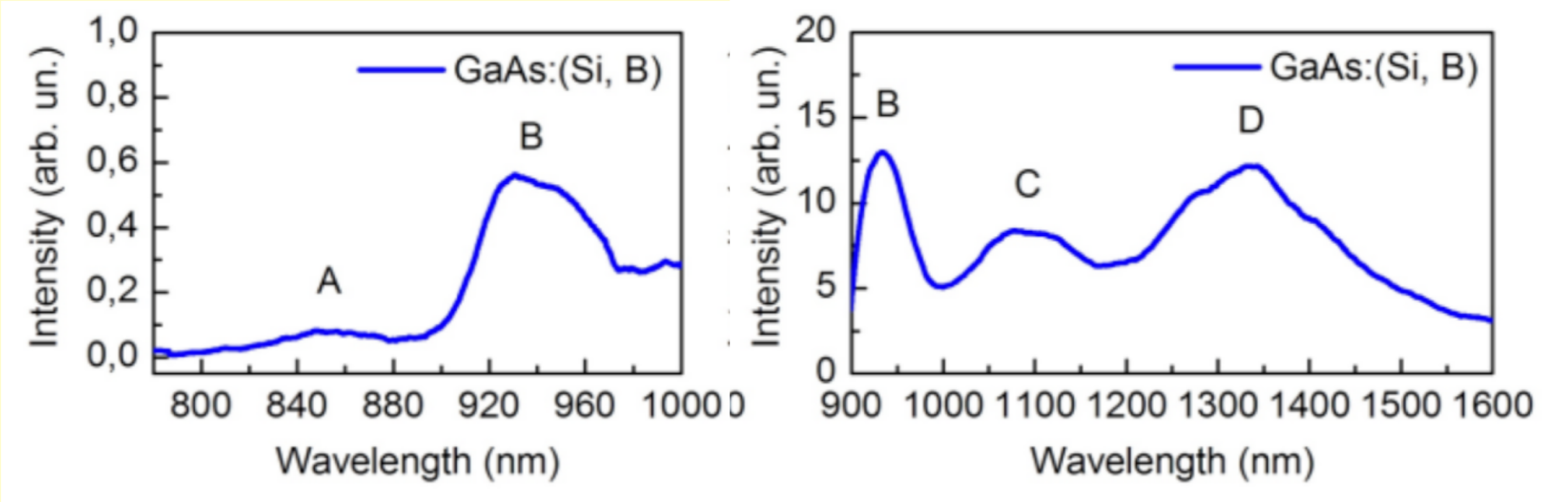
GaAs(Si,B) Emission Spectrum (50 kVp X-rays)



S. Vasiukov, F. Chiossi, C. Braggio, G. Carugno, F. Moretti, E. Bourret, and S. Derenzo, "GaAs as a Bright Cryogenic Scintillator for the Detection of Low-Energy Electron Recoils From MeV/c2 Dark Matter", IEEE Trans Nucl Sci **66,** 2333 (2019). arXiv: 1904.09362

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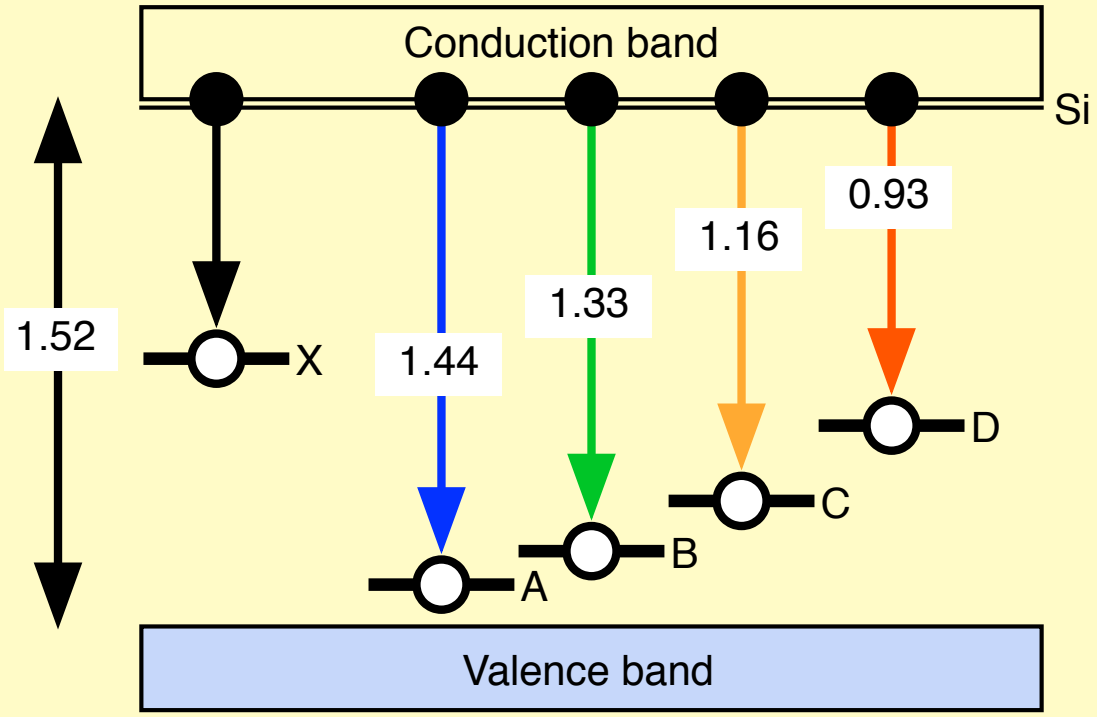
How does GaAs Work as a Scintillator?

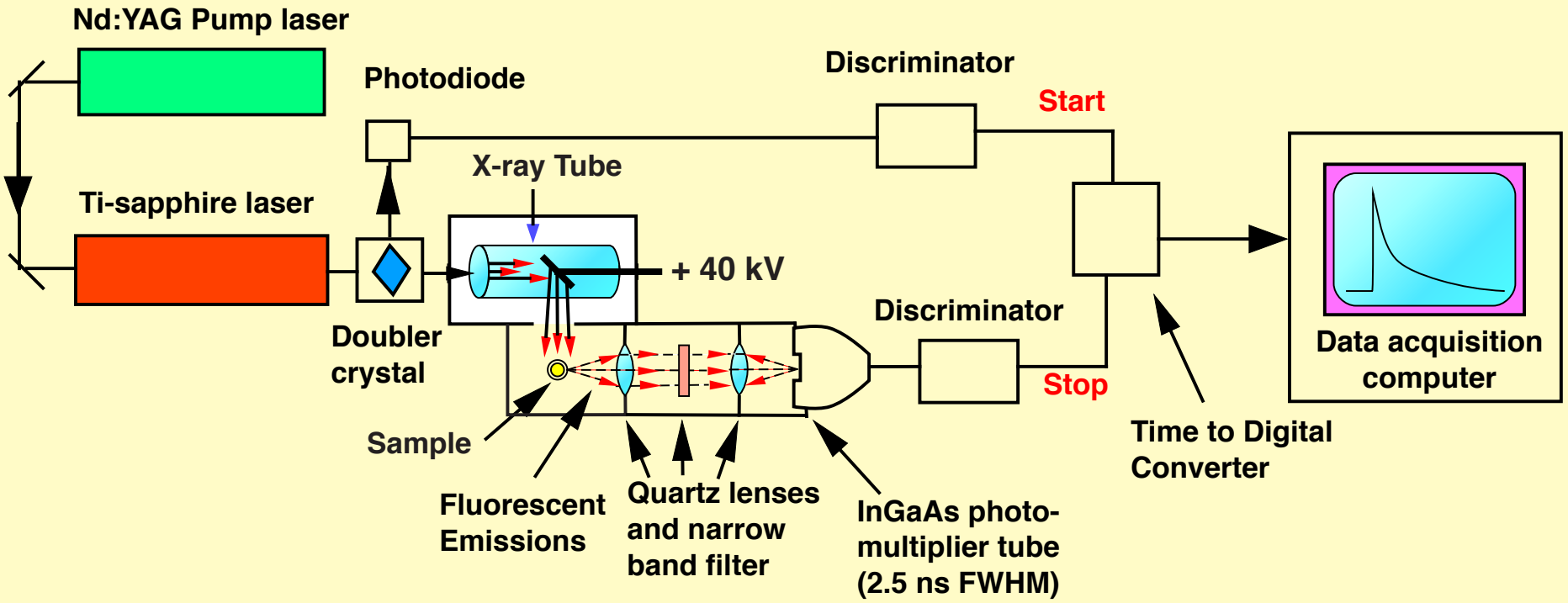


N-type- Fermi level bottom CB
Donor electrons – Si 2 meV binding
All electron traps filled

Radiative process:
1) Electronic excitation makes VB hole
2) VB hole trapped on ABCD sub-ns
3) Radiative recombination ABCD

Emission band peaks:
A 860 nm
B 930 nm
C 1070 nm
D 1335 nm

Pulsed X-Ray Facility
(LBNL Scintillator Research Group)



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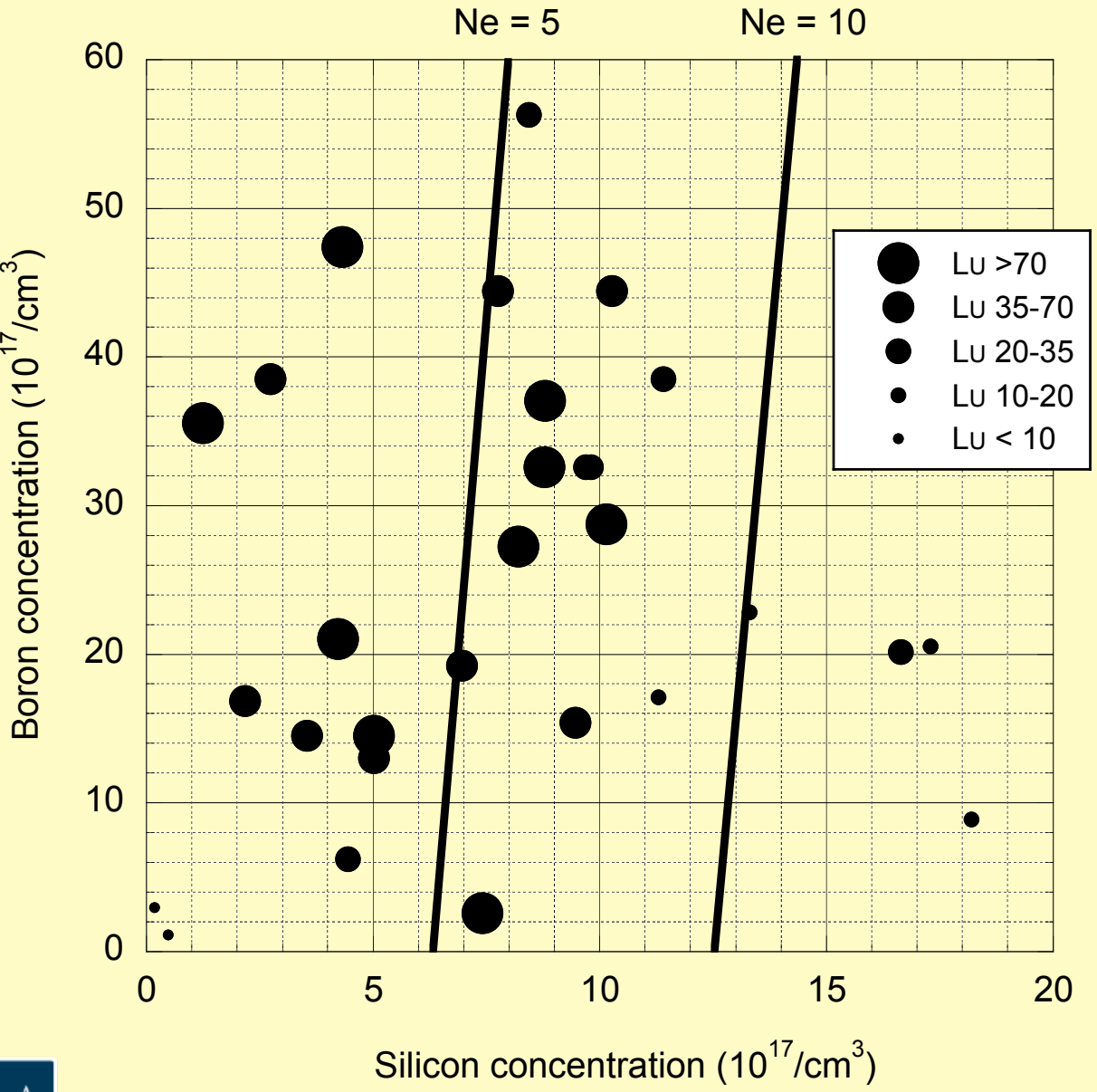
Total Luminosity vs. silicon and boron for 29 samples



Nine have > 70 photons/keV

Two have = 118 photons/keV

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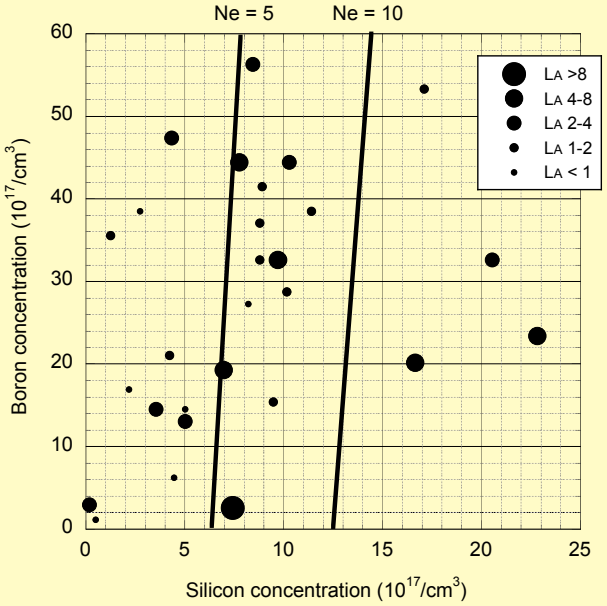
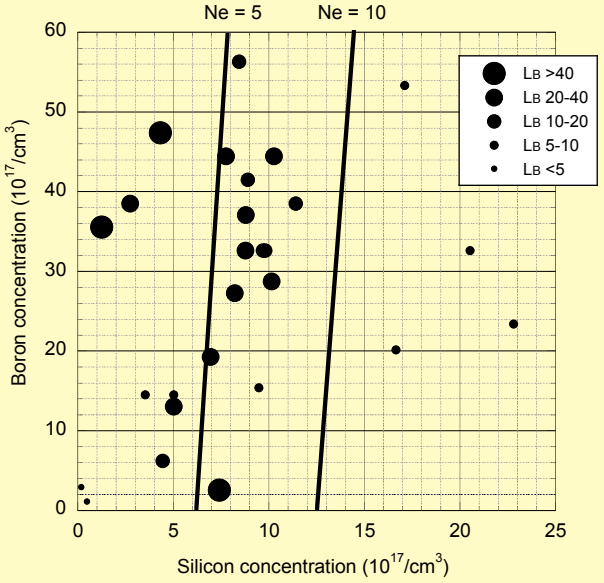
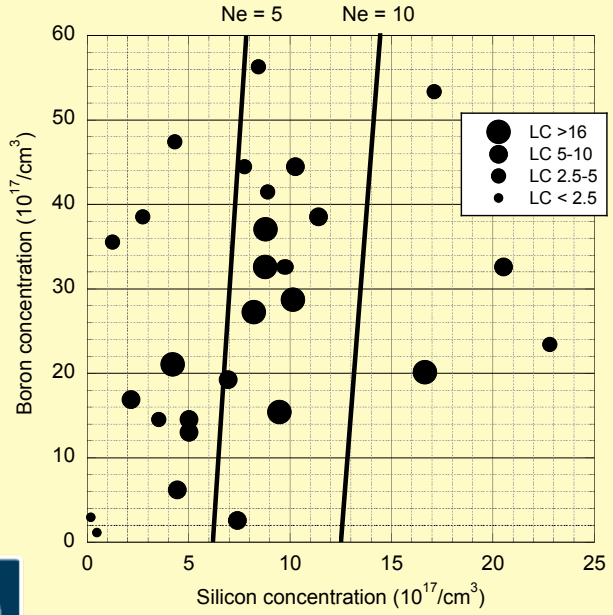
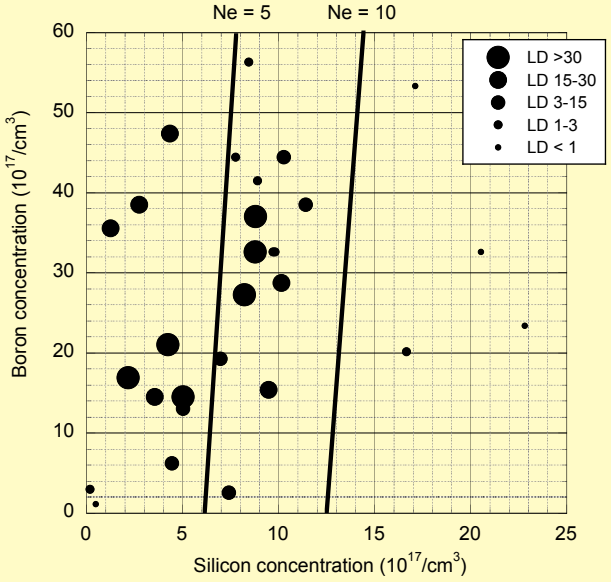
Emission Band A, B, C ,D Luminosities

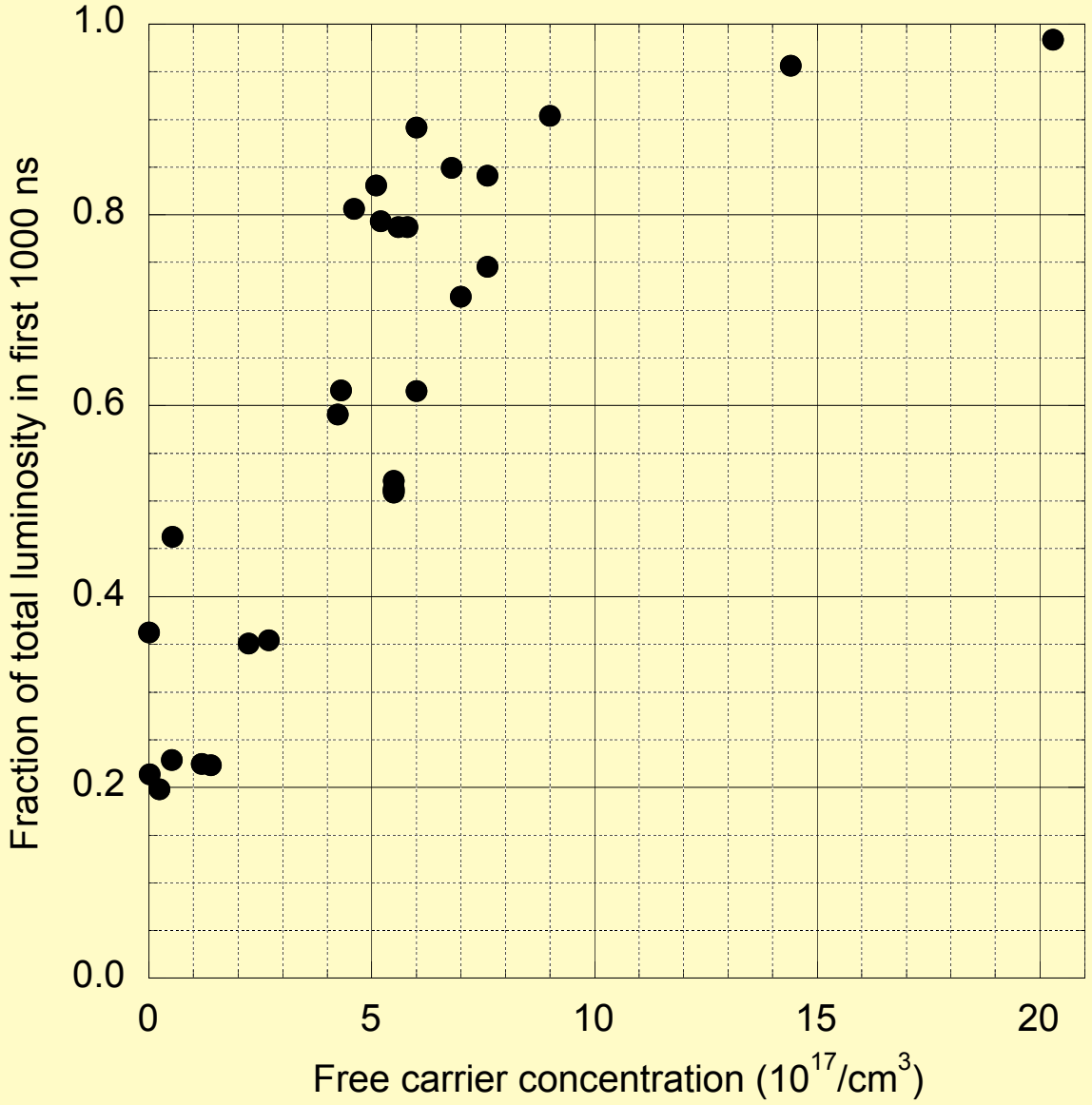




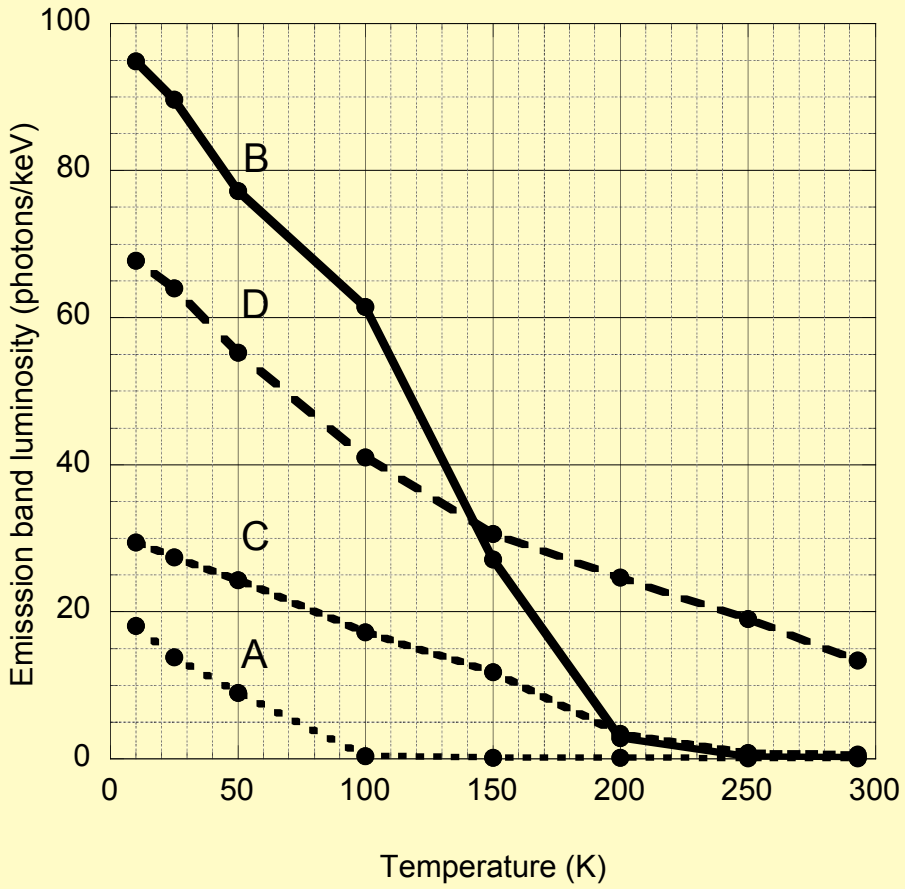


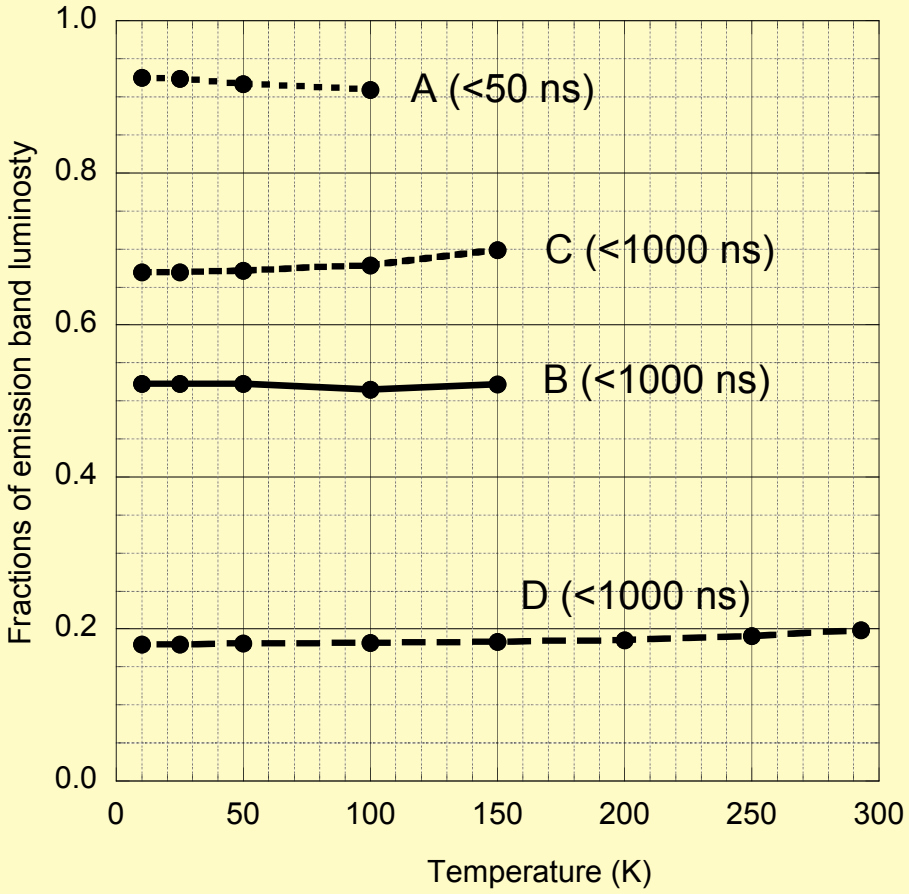


Fraction of total luminosity in first 1000 ns



Temperature quenches the luminosity but does not change the decay times





Thermal quenching decreases the luminosities of all four emission bands but does not change their decay times. This means that the transfer of valence band holes to radiative acceptors (a process that occurs in less than 1 ns) is thermally quenched and that the radiative states are thermally stable.

Conclusions from 29 samples

- 29 samples, nine above 70 photons/keV, two above 115 photons/keV.
- The highest luminosities are 50% of the theoretical limit of 220 photons/keV and are observed without antireflective coatings.
- The luminosities of the four emission bands do not correlate with the concentrations of silicon or boron. This is surprising, since the literature associates band B with boron acceptors and bands C and D with silicon complexes.
- The radiative states do not have characteristic decay times and decrease by about a factor of about 10 as the sample free carrier concentrations increase from $10^{17}/cm^3$ to 2 x $10^{18}/cm^3$. This means that the decay rate is approximately proportional to the spatial density of the delocalized electrons and not bound electrons.
- The rise times for all emission bands is about 0.8 ns, consistent with the response of the phototube. This means that the radiative states are created promptly (sub ns).

Why is GaAs promising for DM Detection?

- There are no naturally occurring radioactive isotopes of Ga or As
- The band gap is 1.52 eV, making possible the detection of electronic excitations from interacting dark matter particles as light as a few MeV/c^2 for electron elastic scattering and a few eV/c^2 for inelastic processes.
- *N*-type GaAs is commercially grown as 5 kg crystals.
- The donor electrons do not freeze out above a free-carrier concentration of 8 x 10^{15}/cm^3.
- Metastable radiative states that could cause afterglow are annihilated by delocalized donor electrons, as evidenced by the lack of thermally stimulated luminescence.
- Luminosities >100 photons/keV are observed without antireflection coatings.

2020 Snowmass Letter of Interest

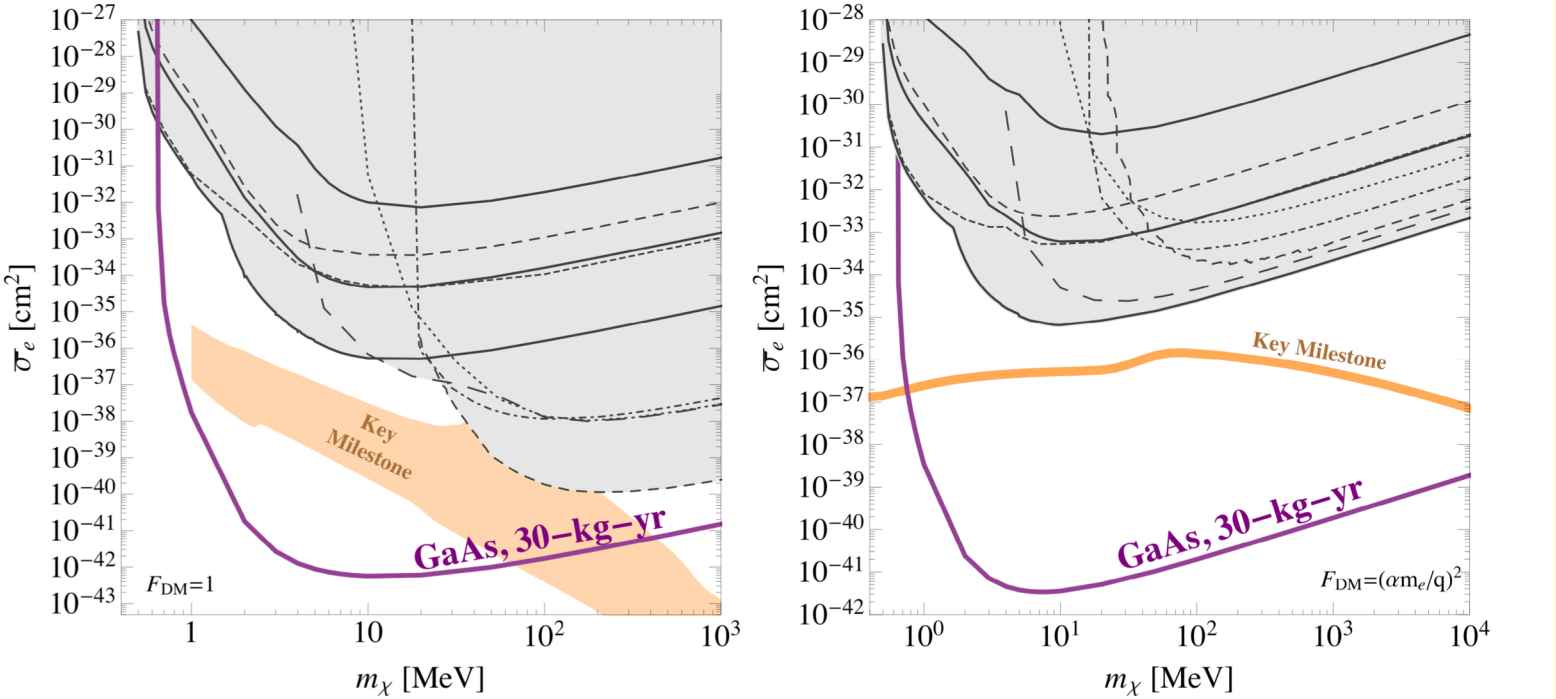
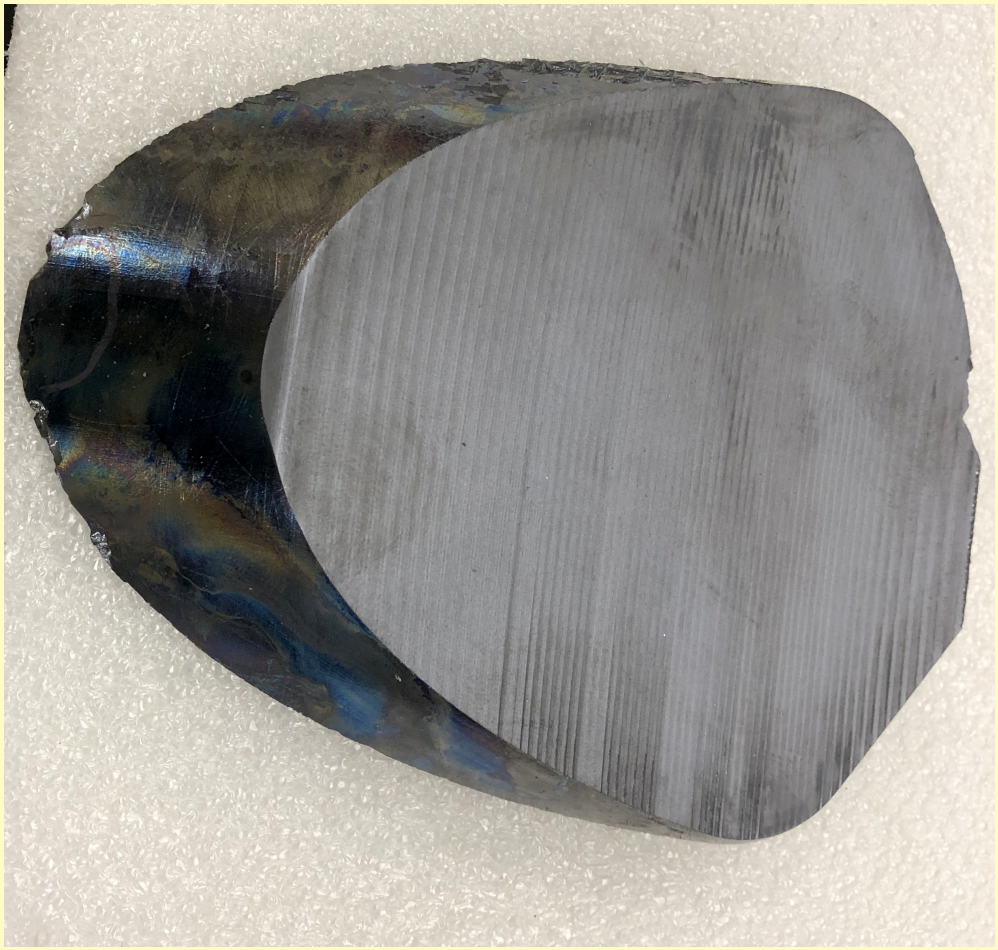


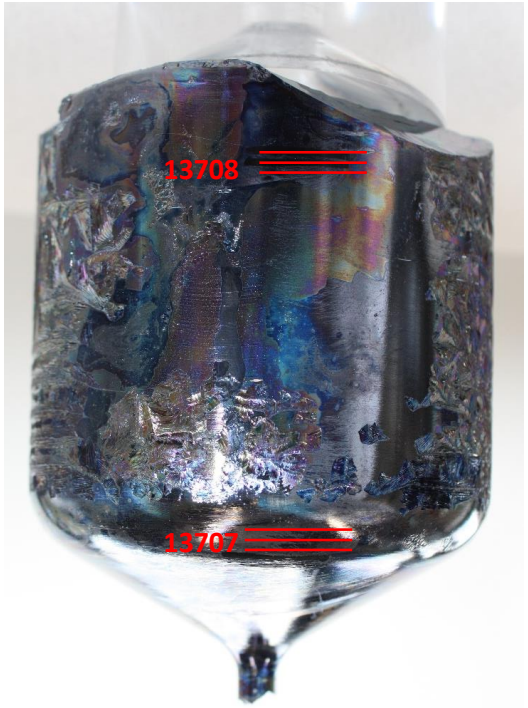
Figure 1: Projected sensitivity (thick magenta line) to dark-matter-electron scattering mediated by a heavy mediator (left) or light mediator (right) of a GaAs target assuming a 30 kg-year exposure. Existing constraints are shown in gray from SENSEI, DAMIC at SNOLAB, XENON10, XENON100, XENON1T, DarkSide-50, EDELWEISS, and CDMS-HVeV10–21. Orange regions labelled “Key Milestone” are from “Basic Research Needs for Dark Matter Small Projects New Initiatives” report Oct 2018

700 g diagonal slice (IKZ boule 24)



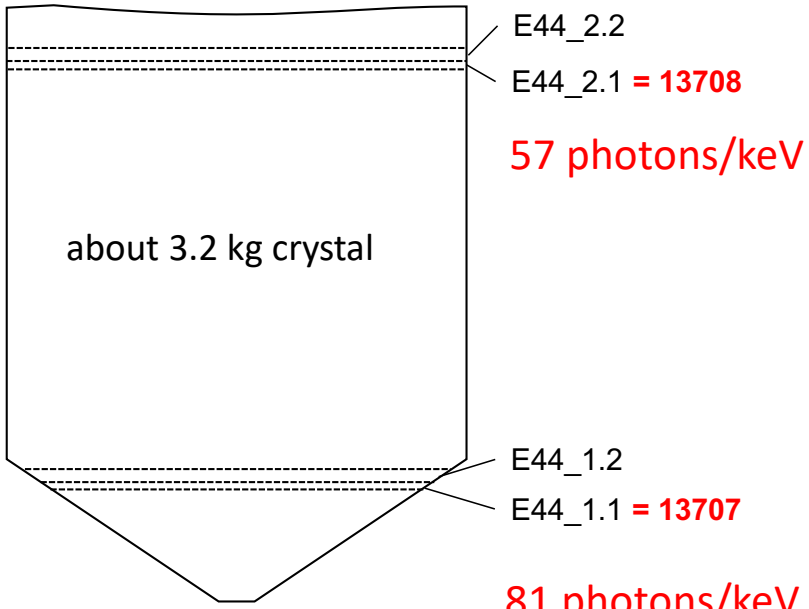
- High Si and B
- Unusually low luminosity
- 11 photons/keV

Large GaAs crystal (IKZ boule 44)



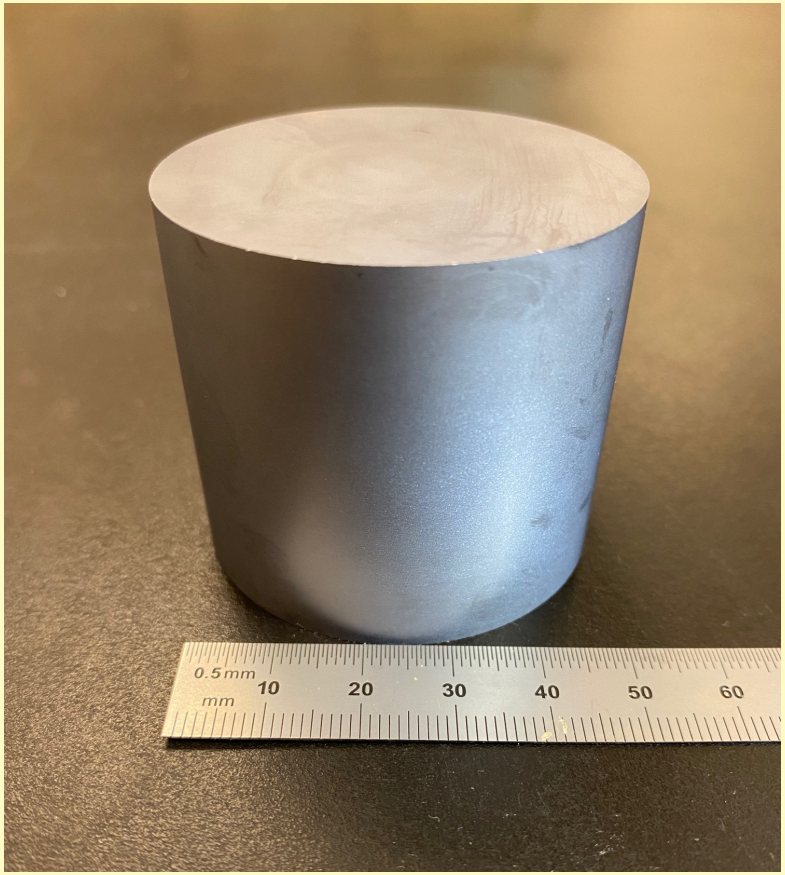
Crystal
E44 (VGF/GaAs) after growth

E44_1.1 & E44_2.1: *d* = 1 mm → Hall, SIMS, Berkeley
E44_1.2 & E44_2.2: *d* = 2 mm → GDMS



Total GaAs initial weight was 5.85 kg.

300 g GaAs (University Wafer)



13719 top of boule
73 photons/keV

13721 bottom of boule
62 photons/keV

To be read out by TES

Future plans

- Read out GaAs with large-area transition edge sensors (Matt Pyle), similar to those used for CDMS.
- GaAs photons => silicon absorber => athermal phonons => superconducting aluminum fins => transition edge sensors
- **Very recent paper:**
  C. W. Fink, S. L. Watkins, T. Aramaki, P. L. Brink, J. Camilleri, X. Defay, Ganjam, Y. G. Kolomensky, R. Mahapatra, N. Mirabolfathi, W. A. Page, R. Partridge, M. Platt, M. Pyle, B. Sadoulet, B. Serfass, and S. Zuber, "Performance of a Large Area Photon Detector For Rare Event Search Applications", arXiv **2009.14302v1** (2020).
- How do the photons avoid internal trapping?
  Measure elastic scattering and loss using an integrating sphere with sample at center.

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Acknowledgments

- UC Berkeley and LBNL: Edith Bourret, Stephen Hanrahan, Federico Moretti, Drew Onken, Maurice Garcia-Sciveres, Matt Pyle
- Stony Brook: Rouven Essig
- IKZ Berlin; Christiane Frank-Rotsch
- DOE BES and HEP support

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Thank You for Your Attention

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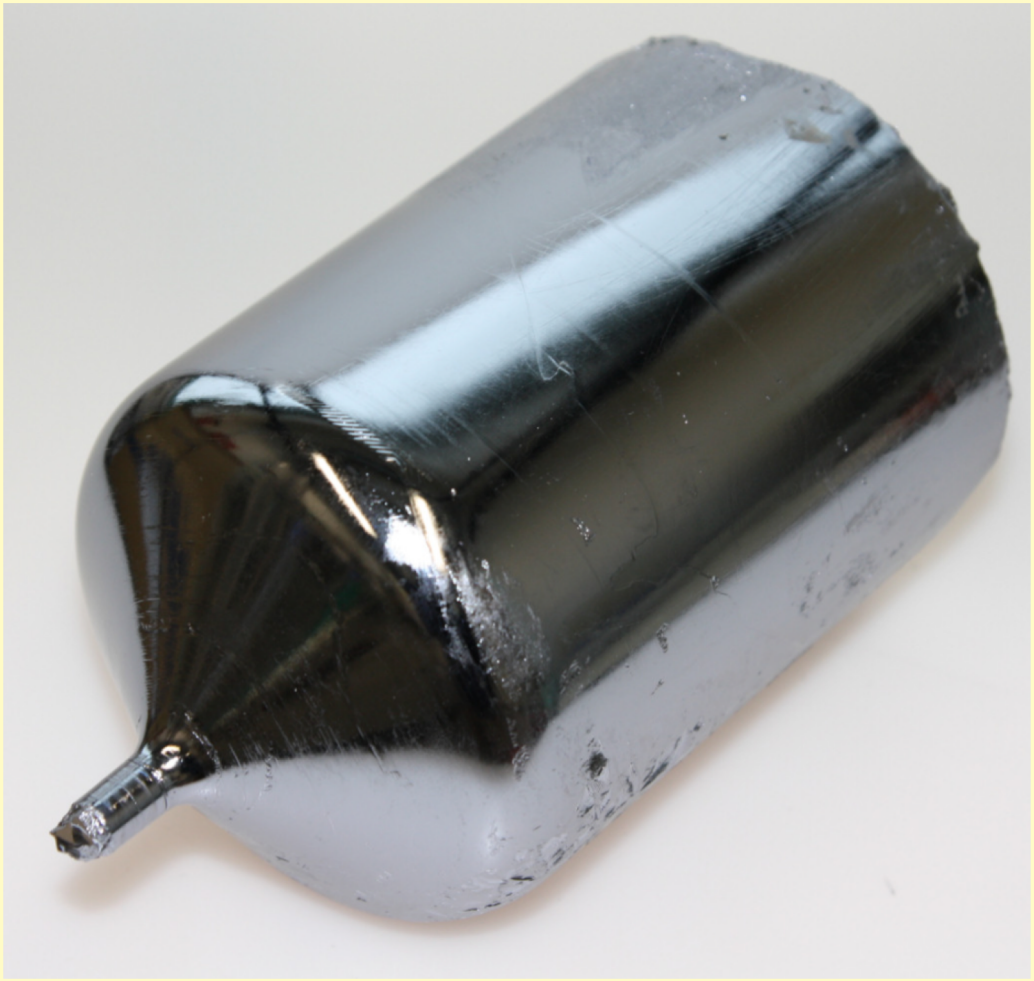
Large GaAs crystals of high purity commonly grown



10 cm GaAs crystal (~5 kg) grown at the Leibniz-Institut für Kristallzüchtung (IKZ), Berlin, Germany

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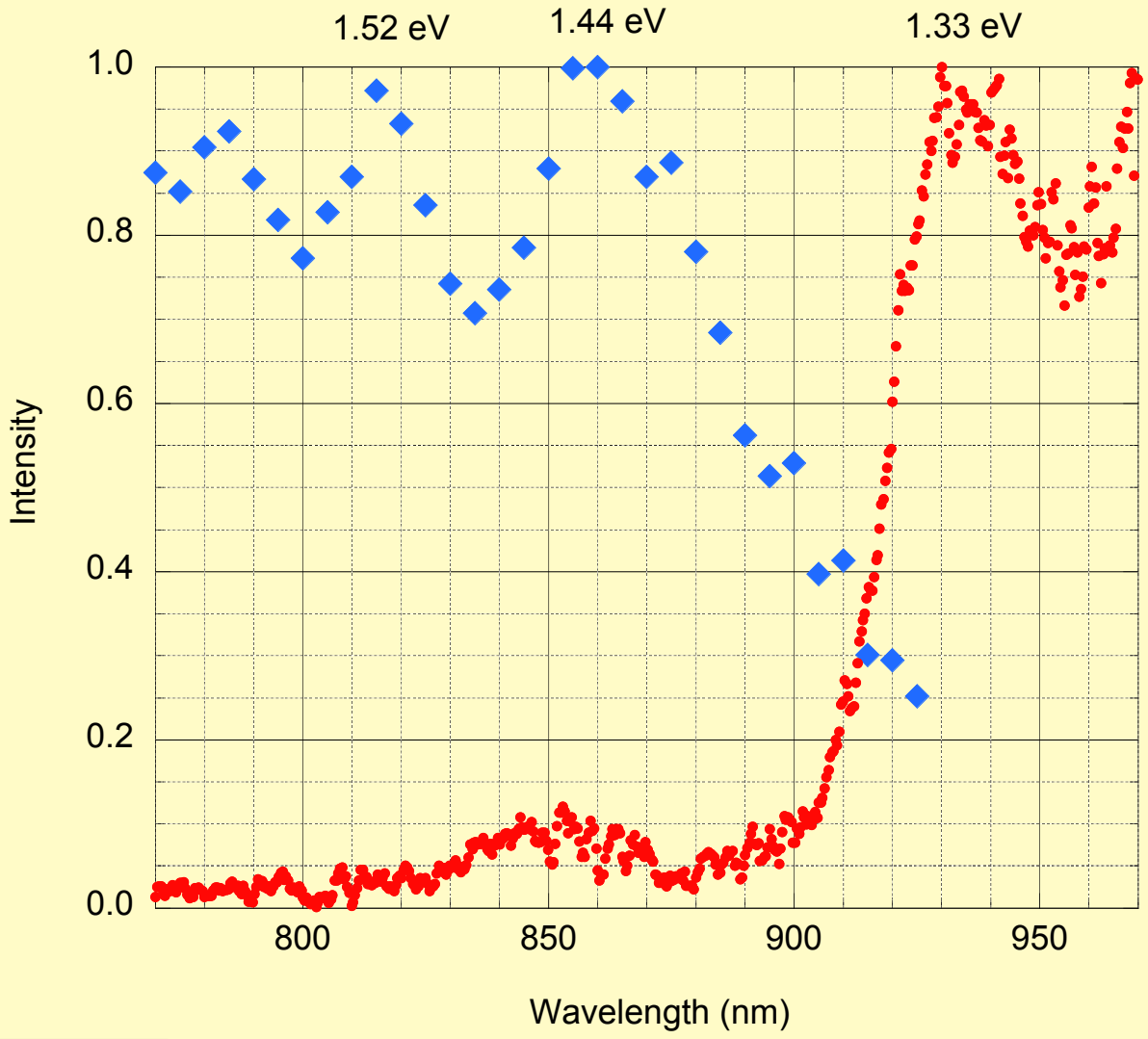
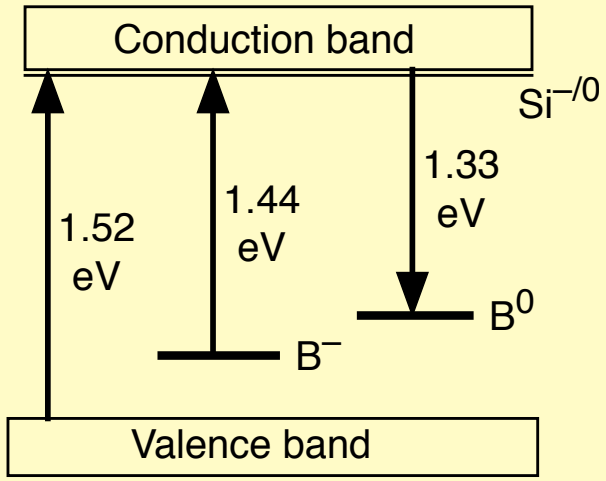
GaAs optical excitation/emission spectra at 10K





- Silicon and boron doping essential
- All electron states filled below conduction band
- Boron efficient hole trap
- 1.5 eV recoil electron threshold
- Stokes shift 0.11 eV
- Low self-absorption

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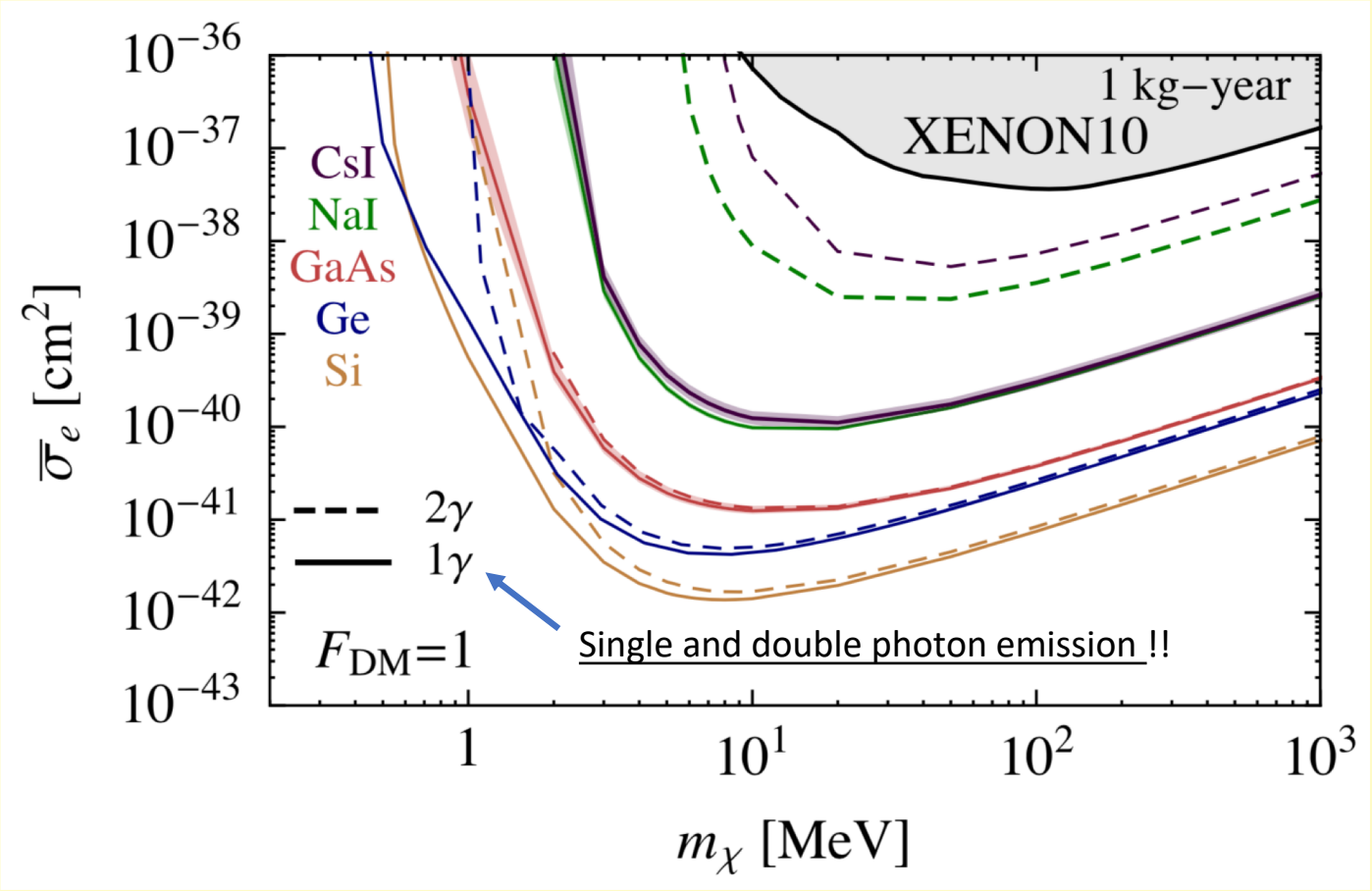
Quantum kinetic calculations for electron recoil detection in scintillators

"Direct Detection of sub-GeV Dark Matter with Scintillating Targets" arXiv:1607.01009 (2017)



For light DM, ER energies can be much greater than NR energies; but only enough for a few photons (eV vs. meV)

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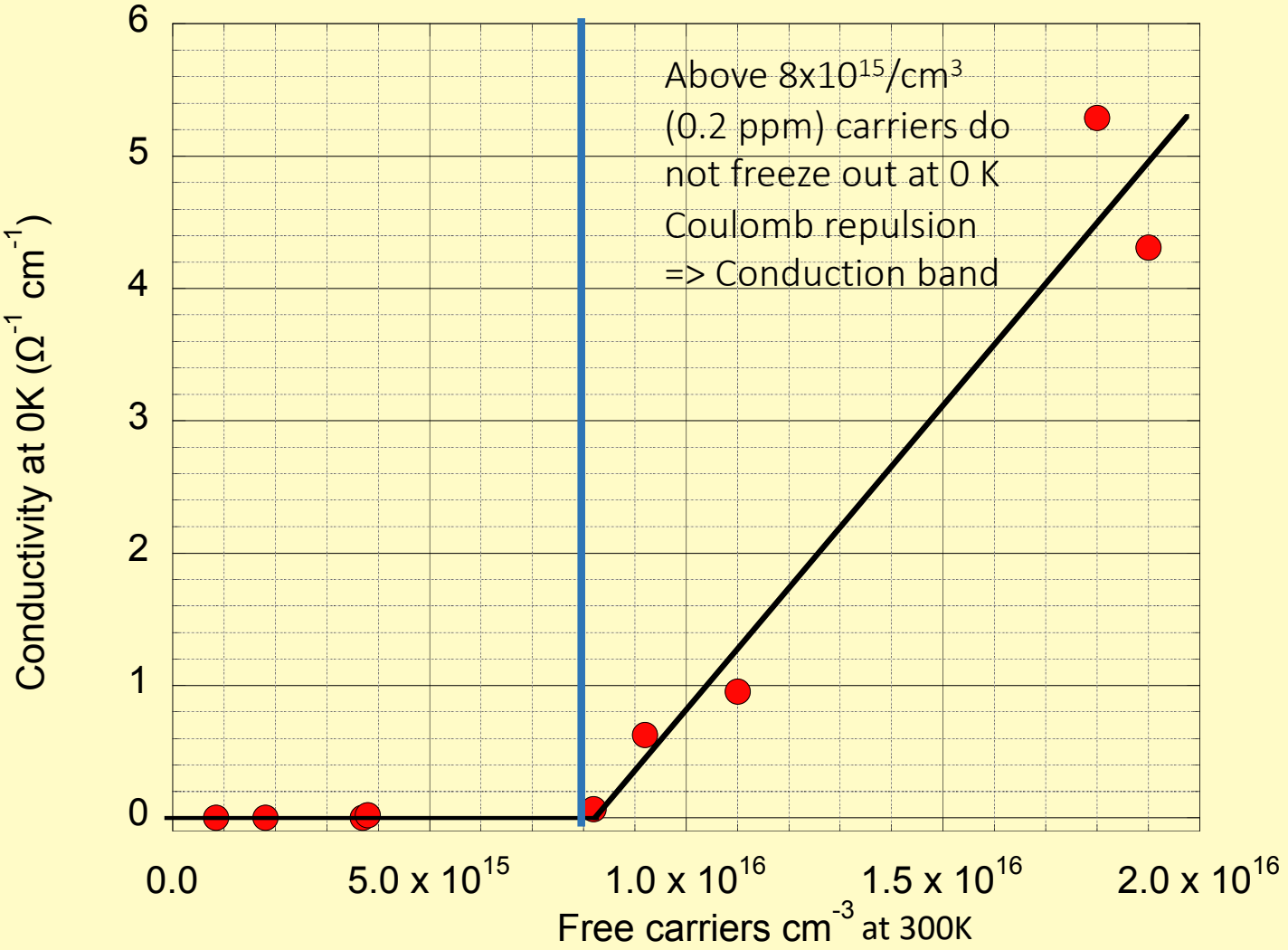
Mott Metal-Insulator Transition in *n*-type GaAs(Si)



Data from Benzaquen et al. "Conductivity of n-type GaAs near the Mott transition" Phys Rev B 36 (1987)

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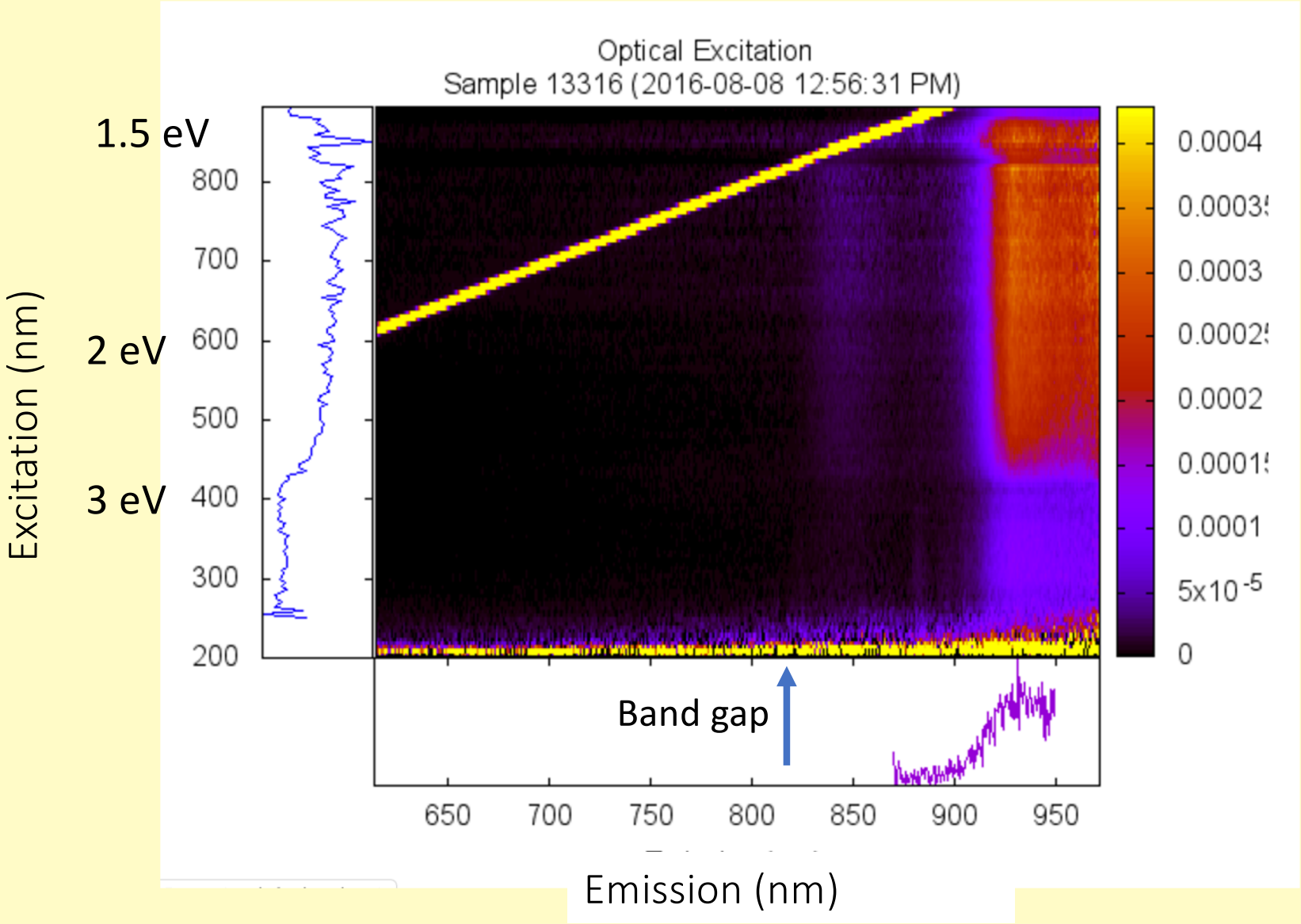
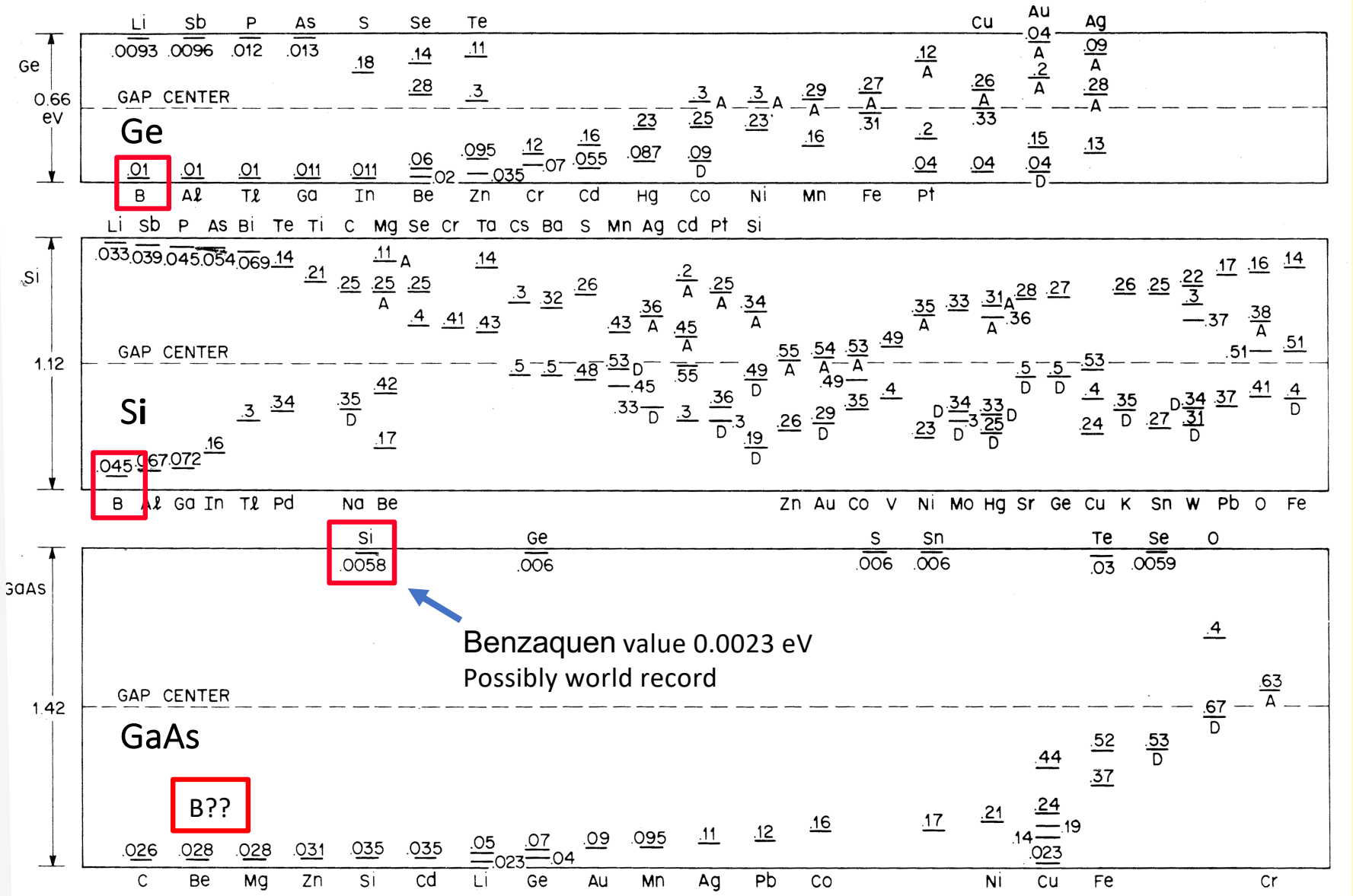
Optical Excitation/Emission Spectra 10K



Donor and Acceptor Ionization Energies in Si, Ge, GaAs